Strong vortex pinning in the low–temperature superconducting phase of $(U_{1-x}Th_x)Be_{13}$

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We have found a sharp transition at $T_{c2} = 350\,mK$ in the vortex creep rate of a single crystal of $(U_{1-x}Th_x)Be_{13}$ with $T_c = 523\,mK$ (x = 0.0275). For $T \ll T_{c2}$, no creep of vortices is observed in a time scale of 10^5 s, while for $T_{c2} < T < T_c$, vortices creep at very high rates (30 % of decay from a metastable configuration in the first 10^5 s at $T = 400\,mK$). The sharp transition occurs at the same temperature at which the second jump in the specific heat appears in these samples. Similar low levels of creep rates have been reported by us in the low–T superconducting phase of UPt_3.[1]

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1. INTRODUCTION

Recent studies of vortex dynamics have uncovered a novel type of exceedingly strong vortex pinning not observed in any other hard type II superconductor.[1] In the low–temperature, low–field superconducting phase of UPt_3, the so–called B–phase, metastable configurations of vortices do not creep towards equilibrium in a time scale of $10^4 - 10^5$ s. However, in the high temperature A–phase, vortex creep occurs with rates that increase rapidly as the temperature is increased. The transition from one creep regime to the other is very sharp and more than two orders of magnitude in size. The anomalous strong pinning detected only in the B-phase, indicates that this superconducting phase supports novel types of vortices and/or novel types of pinning structures.

The only other known example of a superconductor with more than one superconducting phase is thorium–doped UBe_{13}. In the concentration range

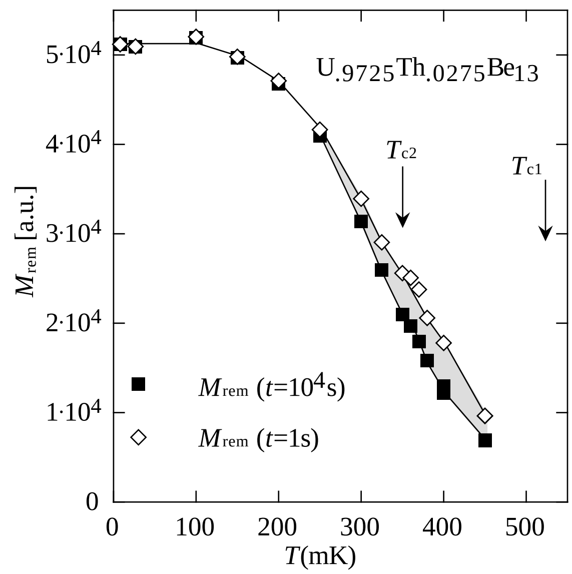

Fig. 1. Remanent magnetization of $U_{.9725}Th_{.0275}Be_{13}$ at two different times as function of temperature. The lines are guide to the eyes.

$0.019 \leq x \leq 0.045$, the heavy fermion $(U_{1-x}Th_x)Be_{13}$ shows an additional second order transition below the onset of superconductivity as first seen in specific heat measurements.[2] Moreover, the lower critical field H_{c1} shows a sudden break in slopes, indicating a clear increase in the superconducting condensation energy below the transition at T_{c2}.[3] Muon spin relaxation data[4] reveal the existence of weak magnetic correlations in the low-T phase which are interpreted as evidence that this phase breaks time reversal symmetry.

Here we discuss the results of a recent investigation of vortex dynamics in a single crystal of $(U_{1-x}Th_x)Be_{13}$ with $x = 0.0275$. Similar results as the ones presented here were obtained with a second single crystal from a different batch. We also compare the data on vortex creep with data on pure UBe_{13} and UPt_3.

2. EXPERIMENTAL ARRANGEMENT

The sample investigated consisted of a single crystal $(U_{1-x}Th_x)Be_{13}$ with $x = 0.0275$ prepared at Los Alamos National Laboratory. It was cut in the form of a parallelepiped $2.25 \times 1.00 \times 0.88\,\mathrm{mm}^3$ in size. It has a transition temperature $T_c = 523$ mK with a width $\Delta T_c = 67\,$mK taken with the $10 - 90\%$ criterion.

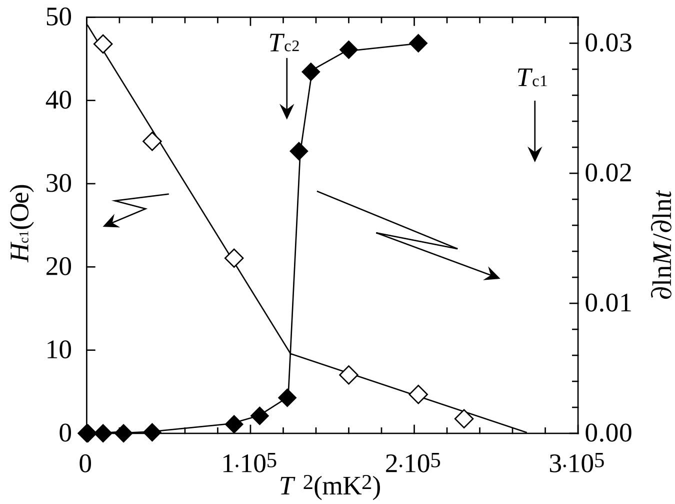

Fig. 2. Initial creep rates (right scale, solid diamonds) and lower critical field H_{c1} (left scale, open diamonds) of $U_{.9725}Th_{.0275}Be_{13}$ as function of T^2

Vortex creep data was obtained from the relaxation of the remanent magnetization after cycling the zero-field cooled sample in high enough fields so that the critical state was established. The relaxation measurements were done from 1 s to $10^4 - 10^5$ s in the temperature range $5\,\mathrm{mK} \leq T \leq T_c$. The experimental arrangement is described in reference 1.

3. RESULTS AND DISCUSSION

In Fig. 1 we show values of the remanent magnetization of $(U_{1-x}Th_x)Be_{13}$ at two different times as function of temperature. The shadowed area indicates the amount of flux that leaves the specimen from the initial time of our measurement ($t \approx 1\,\mathrm{s}$) to $t = 10^4\,\mathrm{s}$. As can be clearly seen, deep in the low-temperature superconducting phase, no flux leaves the sample on a time scale of 10^4 s. On the other hand, in the high temperature phase, considerably amount of vortices leave the specimen in the time indicated. The initial creep rates from the data in Fig. 1 are plotted in Fig. 2. In this figure we also show the measured values of the lower critical field H_{c1} for the same crystal as function of T^2. The sharp break of the H_{c1} slope at $T = 350\,\mathrm{mK}$ occurs at the same temperature as the jump in the specific heat at T_{c2}.[5] At this same temperature we observe a large transition from vortex creep rates $\partial \ln M/\partial \ln t$ of the order of 3×10^{-2} to values as small as $\partial \ln M/\partial \ln t \approx 10^{-5}$. This last figure reflects the limit of our sensitivity, determined mainly by the reproducibility of the background creep of the

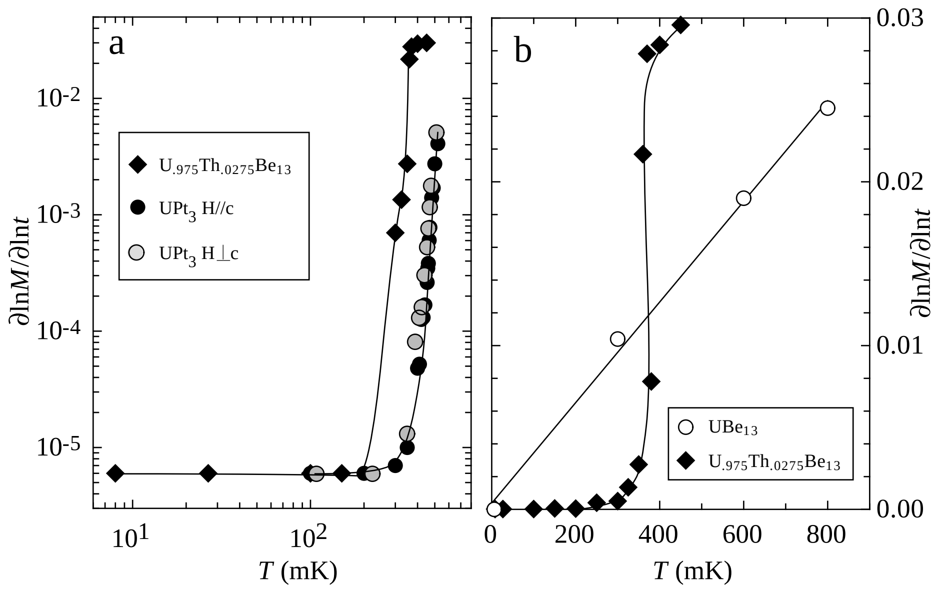

Fig. 3. a. Transition of vortex creep rates in $U_{.9725}Th_{.0275}Be_{13}$ and in UPt_3
b. Creep rates in $U_{.9725}Th_{.0275}Be_{13}$ and in pure UBe_{13}

NbTi coil used to produce magnetic fields of the order of few hundred Oe. This coil is directly attached to the walls of the Epoxy mixing chamber.

In Fig. 3 a we compare the vortex transition in $(U_{1-x}Th_x)Be_{13}$ with similar transitions in UPt_3[1] on a double logarithmic scale. Indeed, in both superconductors one detects "ideal pinning" in their low temperature phases. However, although we do not observe creep on a scale of 10^5 s at the lowest temperatures, we detect some sort of "avalanche" or non logarithmic creep at times which become shorter and shorter as the temperature approaches T_{c2}. The data in Fig. 2 and Fig. 3 are based on the initial logarithmic slope calculated from the first couple of decades in time.

It is interesting to compare the vortex dynamics in pure UBe_{13} with the dynamics of $(U_{1-x}Th_x)Be_{13}$ with $x = 0.0275$ in view of some recent investigation by Kromer et al.[6] From thermal expansion measurements on samples of UBe_{13} with different thorium concentrations, these authors concluded that the nature of the superconducting state in the critical concentration range $(0.019 \leq x \leq 0.045)$ below T_{c1} is not fundamentally different from that in the pure compound below T_c.

In Fig. 3 b we show that the vortex creep rate in a single crystal of pure UBe_{13}[1] follows a well defined linear in T dependence from $T = 5$ mK up to $T \approx T_c$ as expected from the Kim–Anderson theory of thermally activated

creep. No indication of anomalous strong pinning is detected in this material. Indeed there is a fundamental difference between the low–T superconducting phase of $(U_{1-x}Th_x)Be_{13}$ with $x = 0.0275$ and pure UBe_{13} concerning vortex dynamics.

At this point the physical origin of "ideal pinning" is not known. However, by analogy with the superfluid phases of liquid ^{3}He, where broken symmetries are manifested in new physical properties of the quantized vortex lines under rotation, one has to expect that in superconductors with nonscalar order parameters new types of vortices can also lead to unusual behavior.

In conclusion, we have found in UPt_3 and $(U_{1-x}Th_x)Be_{13}$ with $x = 0.0275$ sharp transitions of about three orders of magnitude in the vortex creep rates at the temperature marking the boundary between their two low-field superconducting phases. In both materials, deep in the low–T phases no creep is observed on a scale of 10^5 s. Theoretical input is needed to determine the physical origin of our observation.

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